AN EXPERIMENTAL INVESTIGATION OF
THE EFFECTS UPON LIFT OF A GAP
BETWEEN WING AND BODY OF A
SLENDER WING-BODY COMBINATION
AT MACH NUMBER 1.9

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GAP - GAP
LIF - LIFT
WIN - WING

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SUMMARY

An experimental investigation was conducted to determine the effects upon lift of a streamwise gap between the wing and body of a slender wing-body combination at a Mach number of 1.9. The model was a cone-cylinder body combination with low aspect ratio delta wings. Two sets of wings were employed in an effort to establish the relative magnitude of gap effect for subsonic and supersonic leading edge wings. Data were obtained for body angles of attack up to ten degrees, with and without wing incidence of five degrees.

The experimental results were compared with the linearized, non-viscous, incompressible theory of Ref. 1. The loss in lift due to gap effects was found to be substantially less than that predicted by theory over the entire range of gap parameters tested. It was believed, although not definitely established, that viscous effects were primarily responsible for the deviation from theory. Loss of lift increased with increasing gap, as predicted by theory.

Theory also predicted that for a given gap width the loss in lift would be greater if both wing and body were at an angle of attack than when only the wing had incidence. In the experiment, opposite results were observed.

The percentage loss in lift was found to decrease with increasing angle of attack for the range of the angles studied, with or without wing incidence.

No evidence was found to indicate that gap effects are more pronounced for subsonic leading edge wings than for wings with a supersonic leading edge. However, the two sets of wings tested were of different span, and slender body gap theory indicates that lift variation with gap is dependent upon the slenderness of the body relative to wing semispan. Since the portion of the loss in lift attributable to each of these parameters could not be identified, no conclusions were drawn with regard to either.

As predicted by theory, the effectiveness of a wing as a control surface was found to decrease with increasing ratios of body radius to wing semispan.

For the wing-body exclusive of body nose, control effectiveness was found to decrease with increasing gap, contrary to theory. In the theoretical development, the after body was also excluded.

The control effectiveness parameter also decreased with increasing gap when the body nose was included. Theory indicated that control effectiveness might increase or decrease, depending on

whether the ratio of body radius to wing semispan was small or large.

SYMBOLS

C_L	lift coefficient, $\frac{L}{qS}$
C_N	normal force coefficient, $\frac{N}{qS}$
g	gap width between wing panels and fuselage
L	lift force
N	normal force
q	free-stream dynamic pressure, $1/2\ \rho_o V_o^2$
r_o	radius of cylinder
s_o	maximum wing semispan
s_o^*	wing semispan with zero gap
S	combined wing panel area
V_o	free-stream velocity
α	angle of attack of body axis
δ	wing incidence angle with respect to body axis
ρ_o	free-stream density

AN EXPERIMENTAL INVESTIGATION OF THE EFFECTS UPON LIFT OF A GAP BETWEEN WING AND BODY OF A SLENDER WING-BODY COMBINATION AT MACH NUMBER 1.9

INTRODUCTION

Modern high speed aircraft and guided missiles generally employ all movable lifting surfaces, which provide more effective control, and can be made thinner and stronger than conventional control surfaces. This configuration requires a finite streamwise gap between the fuselage and the lifting surface for mechanical reasons. If the fuselage is curved, there is an additional geometric gap caused by surface deflection which is variable in the chordwise direction. This additional gap is illustrated in Fig. 1.

Non-viscous theory (Ref. 1) predicts large losses in lift, even for very small gaps, but anticipates that the losses would be reduced in practice by the effects of viscosity and possibly compressibility. A shock wave will increase the boundary layer thickness and thus decrease the effective gap, although there may be other compensating compressibility effects. Several other theoretical investigations of gap effect have been made, notably Ref. 2 and 3, but a relatively small amount of experimental data

is presently available concerning streamwise gaps at supersonic speeds.

The purpose of the present investigation was to determine the loss of lift due to streamwise gaps for a cone-cylinder body combination with low aspect ratio delta wings at various angles of attack, with and without wing incidence, at a nominal Mach number of 1.90. As a secondary objective, it was desired to determine the relative magnitude of the gap effect with both subsonic and supersonic leading edge wings. Therefore, two sets of wings were tested at this Mach number.

The investigation was conducted in the University of Michigan 8 x 13 inch supersonic wind tunnel in February 1955, with the assistance of Lieutenants R. C. Wood and B. J. Cartwright, U. S. Navy, who were concurrently conducting a turbulent boundary layer investigation with the same model. (Ref. 4). The work was performed as a part of the third year curriculum in Aeronautical Engineering of the U. S. Naval Postgraduate School, Monterey, California, and was financed by the Bureau of Aeronautics, Navy Department, Washington, D. C.

We wish to thank Dr. H. P. Liepman, director of the University of Michigan Supersonic Wind Tunnel, for his advice and assistance at all stages of the investigation, and Dr. A. M. Kuethe, Felix Pawlowski Professor of Aerodynamics at the University of Michigan, for his assistance with slender body theory and many valuable suggestions in connection with the interpretation of results.

EQUIPMENT AND PROCEDURE

The model consisted of an aluminum cone-cylinder body combination with double wedge delta wings fabricated of tool steel. Two sets of wings with equal root chords were employed. Each set of wings had different sweepback angles so that both the subsonic and supersonic leading edge cases could be studied at the same Mach number. A sketch of the wings and body combination is included as Fig. 2.

The model was mounted on a steel cantilever sting fitted with two sets of four Baldwin SR-4 strain gages, each connected as a Wheatstone bridge. Strains produced by bending of the cantilever sting under the action of a normal force on the model appeared as moments on a Sanborn Twin-Viso Recorder. The slope of the resulting bending moment diagram gave the shear, or normal force, on the model. The strain gages were bonded using techniques recommended by the Baldwin Locomotive Works.

Prior to each test run the Sanborn Recorder was balanced to read zero moment at each strain gage station. A weight of three pounds was hung on the model at a point midway between the centers of the strain gage banks; amplification was adjusted as desired and the resulting moments were recorded on the Sanborn tapes. No further adjustment of amplifier gain was made, and thus calibration moment served as a conversion factor for moments recorded during the run. Static tests had established that strain gage

behavior was linear over the entire range of normal forces encountered. The cantilever sting and strain gage arrangement is shown in Fig. 3.

The University of Michigan Department of Aeronautical Engineering 8 x 13 inch supersonic wind tunnel was used with nozzle blocks for a nominal Mach number of 1.90. A complete description of this facility is contained in Ref. 5. The actual Mach number of each test run was calculated from the ratio of static pressure in the test section to total pressure of the source. Dry air with an average dew point of -48° F was used in the tests.

The wings were adjusted with reference to the body using twist drills as gages for gap settings. A height gage was used to set incidence angles.

Angle of attack was changed during each run by an electrically driven support system. The operator attempted to obtain body angles of attack of 0°, 5°, and 10°, and marked the actual angles achieved on a calibrated dial. Generally, it was possible to control the system so as to stop within one quarter of a degree of the desired angle of attack. The data were later adjusted to the reference angles of 0°, 5°, and 10° by a plot of lift versus angle of attack. As the average duration of each run was sixteen seconds, it was possible to remain at each reference angle for about four seconds. The effects of system backlash were avoided by approaching each desired angle of attack from the same direction. Each run was started and stopped with the wings parallel to the flow as a pre-

caution against shearing the wing pins by transient air loads.

A tripper ring, located 1.67 inches from the body nose was employed to insure a turbulent boundary layer over the model for all runs.

The maximum value of gap parameter tested was limited by wing-tunnel wall interference considerations. Because of the presence of the sting along the longitudinal body axis, a maximum wing pin length of .277 inches could be accommodated, of which .200 inches constituted a minimum for adequate bearing surface. Since it was desired to investigate gaps as large as .470 inches, it was necessary to make these runs first and then grind down the pins to the proper length for each successively smaller gap. This situation precluded repeat runs at will, and accordingly an approximate reduction of data was carried out after each run and an immediate decision reached concerning the advisability of a repeat run.

At zero gap, vacuum wax was applied to insure complete sealing of the wing-body juncture.

A photograph of the model is included as Fig. 4, which shows it as arranged for the boundary layer investigation of Ref. 4. A total head probe is mounted in the boundary layer, and the model is rotated 90 degrees from the test position.

Standard Sanborn Recorder tapes of five centimeter width were used. Data readings were estimated to one quarter of a millimeter. No equivalent in pounds can be quoted, as this was a function of amplifier gain and attenuation setting, hence variable. The

most sensitive attenuation (x1) was used to record the output of the forward strain gage set at all angles of attack. However, the magnitude of the output of the rear strain gages was such that a less sensitive attenuation setting (x4) was required when the angle of attack of the body was 5° or greater. The attenuation was therefore shifted at the appropriate point in the run. Amplifier gain was adjusted as necessary between runs.

Three possible sources of error were present in reading the tapes. The first resulted from the estimation of data to 1/4 millimeter, allowing the recorded value to differ as much as 1/8 millimeter from the actual value of the trace. The second source of error was similar but greater in magnitude. Estimation of the calibration moment to 1/4 millimeter introduced a possible error in the conversion constant. The third possible source of error was present in a small minority of the runs, and occurred as a result of a slight shift in the zero reference line during the run. This effect was traceable to saturation at some stage of the run as a result of a belated change of attenuation. The technique adopted in reading the tapes was to use the original zero reference for data recorded prior to saturation and the final zero reference for data recorded after saturation. The maximum possible errors could occur at the highest angle of attack. Under the most adverse conditions, with all three possible errors at maximum values in the same direction, the total error, expressed in coefficient form (C_N), could be as great as ± 0.0147. For the vast majority of the runs, in which

zero shift error did not occur, the maximum error would be approximately ± 0.0100.

It should be stressed that these are maximum errors. If the reading error and error of the constant are in opposite directions, they tend to neutralize each other. Similarly, if the reading errors from the two sets of strain gages are in opposite directions, they tend to cancel out. One set is subject to tension and the other to compression, and the normal force is determined from the slope of the moment diagram. An approximate analysis of the errors and the manner in which they combine indicates that the average reading error probably does not exceed $C_N = \pm 0.0059$ for the 10° angle of attack case and $C_N = \pm 0.0044$ for the data at 5° angle of attack. The average error introduced by angle of attack estimation has an approximate coefficient value of ± 0.0040.

RESULTS AND DISCUSSION

The normal force data obtained are tabulated in Tables I and II. As previously indicated, some modifications of the raw data were necessary to reduce it to the selected reference angles of 0°, 5°, and 10°. The data were further reduced to coefficient form to remove the influence of wing area and Mach number. The normal force coefficients are plotted against gap parameter in Fig. 5. As anticipated, total normal force decreases with increasing gap as a result of increasing tendency toward pressure equalization through the gap.

The terms "normal force" and "lift" have been used interchangeably throughout this report. The quantity actually measured was normal force, which is very nearly equal to the lift for the small angles of attack under consideration.

Theory indicates that beyond certain large values of gap parameter there is essentially no further decrease in the lift. This phenomenom was not encountered in the experiment, as the maximum gap parameter tested was .185. However, it is difficult to visualize the employment of gap parameters greater than .02 in practice.

Figs. 6 and 7 give a somewhat more useful presentation of variation in lift with gap width, as the ratio of lift to lift with zero gap is plotted versus gap parameter, the lift of the cone first having been subtracted. Stone theory (Ref. 6) was used to

compute the lift of the cone at angles of attack of 5^{o} and 10^{o}, and it was then simply subtracted, lift of the cone being invariant with gap according to theory.

For ease of comparison with non-viscous theory, portions of Figs. 3 and 4 of Ref. 1 by Dugan and Hikido have been reproduced in Fig. 7 of this report. It is apparent that the loss of lift due to streamwise gap effects is substantially less than the loss predicted by linearized non-viscous theory. In fact, for practical gap sizes (parameter .02 or less) the loss in lift is less than ten percent for nearly all angles of attack and incidence studied. The suggested reasons for departure from theory are viscous effects, compressibility, wing-body interference, and the approximations introduced in linearized theory.

The theory of Ref. 1 treats the incompressible, inviscid, linearized case. Each of the approximations contributes to the deviation between theory and experiment, but the extent of each contribution cannot be ascertained from the results reported here. Schlieren photographs taken during the experiment and included in Ref. 4 indicate that the portion of the gap behind the wing pin is highly turbulent. It is believed that the main deviation from theory is attributable to viscous effects, both through the presence of the boundary layer and the wake behind the wing pin. However, in any actual missile or aircraft some such supporting arrangement must be present and presumably the effects will be similar.

Dugan and Hikido have indicated that for a given gap

width the loss in lift is more severe when both wing and body are at an angle of attack than when the wing alone has incidence. A comparison of the curves for $\alpha = 5$, $\delta = 0$ and $\alpha = 0$, $\delta = 5$ in Figs. 6 and 7 does not support this conclusion. For both sets of wings tested the losses were slightly greater with incidence alone. The presence of additional geometric gap is not sufficient to produce the difference. For the small angle of incidence used (5°) the additional gap in terms of gap parameter is .003 in the most sensitive situation, (i.e. smallest gap tested) and can be considered negligible. For large angles of incidence, however, geometric gap becomes extremely important.

Since only one value of incidence was tested, $\alpha = 5$, $\delta = 0$ versus $\alpha = 0$, $\delta = 5$ represents the only direct comparison of this type. However, a comparison of the cases of wing and body at 10° angle of attack versus body at 5° angle of attack and wing at 5° incidence logically should be quite similar. The same trend was observed, in that losses were slightly greater where wing incidence was involved.

It was also observed that the percentage loss in lift for a given gap is less severe at the higher angles of attack. This was found to be the case for all configurations tested. A plot of percent loss in lift versus angle of attack for the various gap settings is included as Fig. 8. It may be noted that this decrease in lift loss is opposite to that which would be expected if one considers only the fact that the boundary layer on the body

should become thinner as angle of attack increases.

The results of the study of the effect of subsonic and supersonic leading edge were inconclusive. Bleviss and Struble (Ref. 2) predicted that for a half delta wing adjacent to an infinite wall gap effects would be more pronounced if the leading edge were subsonic. As a minimum requirement to investigate this effect properly, a given wing planform should be tested at two different Mach numbers. Time limitations precluded a change of nozzle blocks, and it was also realized that the correlation between the cone-cylinder body and infinite wall would not be particularly good. Consequently, it was decided to test two sets of wings at the same Mach number. Ref. 1 indicates that lift variation with gap is also dependent on the slenderness of the body relative to wing semispan $\left(\frac{r_o}{s_{o*}}\right)$. For a given gap, and the same body, losses are greater when wings of smaller span are used. There can be no doubt that Dugan and Hikido were considering similar wings. In the present experiment the subsonic leading edge wings also had the lesser span. Both effects should theoretically increase the loss in lift for a given gap, yet there was no pronounced difference between the curves obtained for the small and large wings. Lift loss for the subsonic leading edge wings was slightly greater than for the supersonic wings at the low angles of attack, but the difference decreased with increasing angle of attack, until at the maximum angle investigated, the difference was negligible. Since it was impossible to separate the effects, no

conclusions could be drawn with regard to the importance of either the slenderness parameter or leading edge parameter. It is estimated that the difference in lift ratios to be expected as a result of the difference in span is of the order of one percent. Hence any trends in this connection could easily be obscured by experimental error.

Dugan and Hikido have also plotted the variation of a control effectiveness parameter with gap. The parameter is defined by

$$-\frac{\alpha}{\delta} = \left(\frac{\frac{dC_L}{d\delta}}{\frac{dC_L}{d\alpha}}\right)_{C_L = \text{constant}}$$

and is an indication of the effectiveness of a control surface in producing lift. The results obtained in the present experiment are included as Fig. 9. Again, the applicable portions of the theoretical curves have been reproduced for comparison. For the wing-body exclusive of body nose, agreement with theory is achieved in that for larger ratios of body radius to wing semispan control effectiveness is decreased. However, control effectiveness is found to decrease with increasing gap, contrary to theory. For the wing-body with body nose, control effectiveness is again diminished for increasing ratios of body radius to wing semispan, and also decreases with increasing gap. A consideration of the curves indicates that if the ratio of body radius to wing semispan is further decreased, it is possible that a situation will be reached in which control effectiveness will increase with increasing gap.

CONCLUSIONS AND RECOMMENDATIONS

For the range of gap parameters tested, lift of the wing-body combination decreases with increasing gap, but lift losses are considerably less severe than those predicted by incompressible, inviscid, linearized theory.

For a given gap width, the loss in lift is greater when the wing alone has incidence than when both wing and body are at an angle of attack.

The percentage loss in lift decreases with increasing angle of attack for a fixed gap width.

The effectiveness of a wing as a control surface is decreased for increasing ratios of body radius to wing semispan.

Control effectiveness decreases with increasing gap for the wing-body combinations studied, but it is conceivable that control effectiveness could increase with increasing gap for small ratios of body radius to wing semispan.

Extensive additional experimental investigation is required, particularly in the region of practical gap sizes (gap parameter less than .02). A somewhat wider range of angles of attack and wing incidence should also be studied. To establish the importance of slenderness ratio, either several sets of similar wings could be tested with one body at the same Mach number or several geometrically similar bodies could be tested with one set of wings. Each of these combinations could be tested at two Mach

numbers in an effort to determine the effect of the subsonic or supersonic leading edge.

It is anticipated that the instrumentation problem will be severe in the region of very small gaps. The difference in the lift measured at consecutive gaps during the reported experiment was small, in spite of the relatively coarse gap parameter interval. In order to determine accurately the behavior of the lift ratio curve in the vicinity of the boundary layer, very fine gradations in gap parameter will be necessary, involving extremely small differences in lift.

ADDENDUM

It was not intended to imply that removal of the body nose would make the results of the investigation independent of nose shape. The boundary layer thickness and pressure distribution in the region of the wing are dependent on the body nose shape and the length of the body forward of the wing. However, since a correction for displacement thickness has a negligible effect in bringing the curves closer to theoretical, a change in nose shape, insofar as boundary layer thickness is concerned, is not expected to materially alter the results. Small changes in the pressure distribution caused by changes in the nose configuration should likewise have small effect.

REFERENCES

1. Dugan, D. W., and Hikido, K.: Theoretical Investigation of the Effects Upon Lift of a Gap Between Wing and Body of a Slender Wing-Body Combination. NACA Technical Note 3224, August 1954.

2. Bleviss, Z. O., and Struble, R. A.: Some Effects of Streamwise Gaps on the Aerodynamic Characteristics of Low-Aspect-Ratio Lifting Surfaces at Supersonic Speeds. Douglas Report SM-14627, Santa Monica Division, April 1, 1953.

3. Mirels, H.: Gap Effect on Slender Wing-Body Interference. Reader's Forum, Journal of the Aeronautical Sciences, Vol. 20, No. 8, August 1953.

4. Cartwright, E. J., and Wood, R. C.: An Investigation of the Effect of a Turbulent Boundary Layer Upon the Lift of a Wing-Body Combination with a Gap Between Wing and Body at Mach Number 1.9, May 1955

5. Culbertson, P. E.: Calibration Report on the University of Michigan Supersonic Wind Tunnel, UMM-36.

6. Stone, A. H.: On Supersonic Flow Past Slightly Yawing Cone. Journal of Mathematics and Physics, Vol. 27, p. 67-81. April 1, 1948.

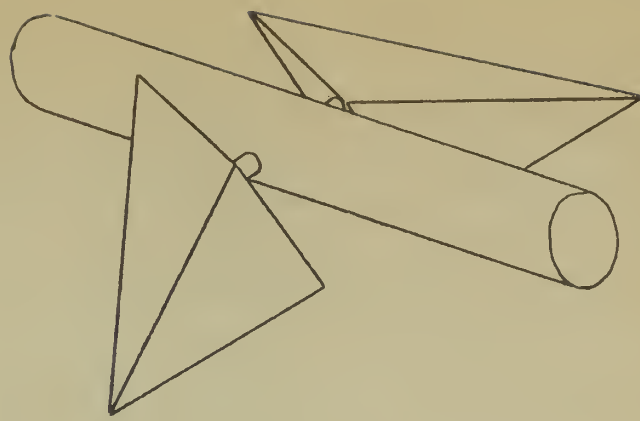


Fig. 1 Geometric Gap

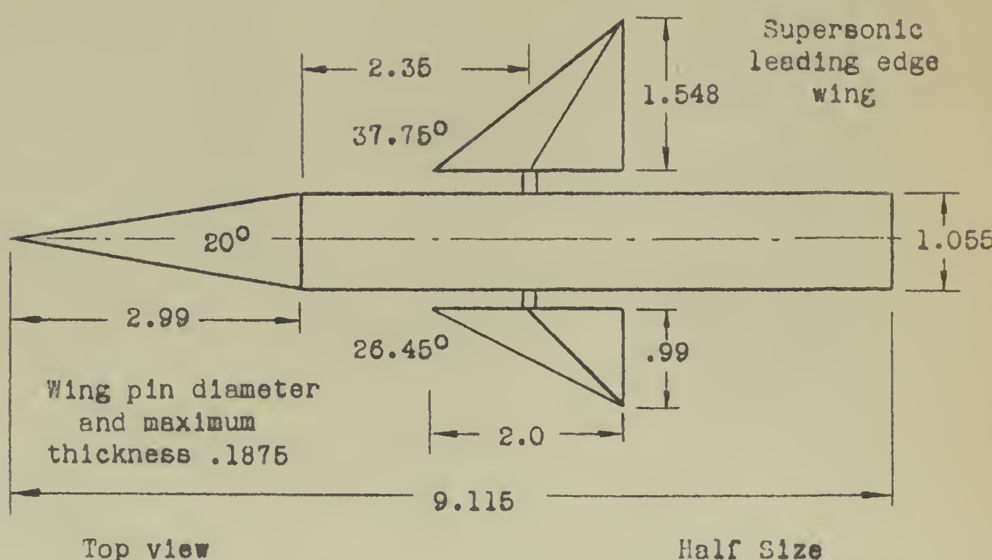
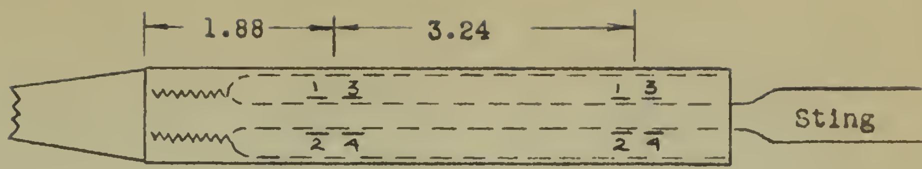
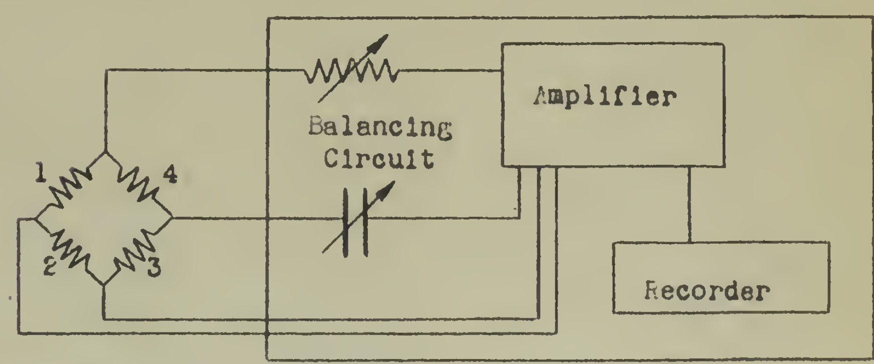


Fig. 2 Test Model



Side View
Model mounted on sting



Strain gage
station

Sanborn recorder

Fig. 3 Sting and Strain Gage Arrangement

FIG. 4 TEST MODEL

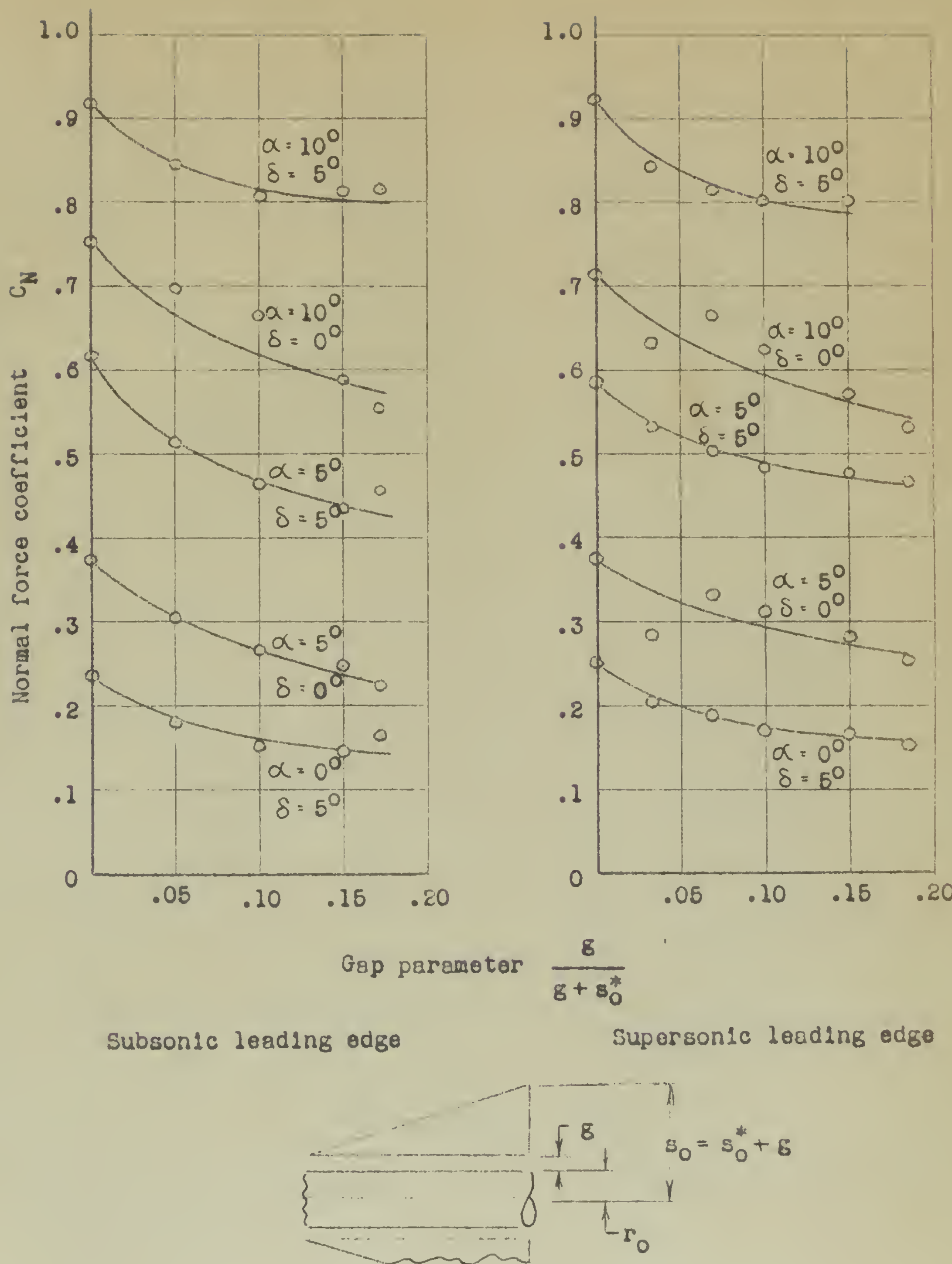


Figure 5. Variation of normal force coefficient with gap for a wing body combination, body nose included.

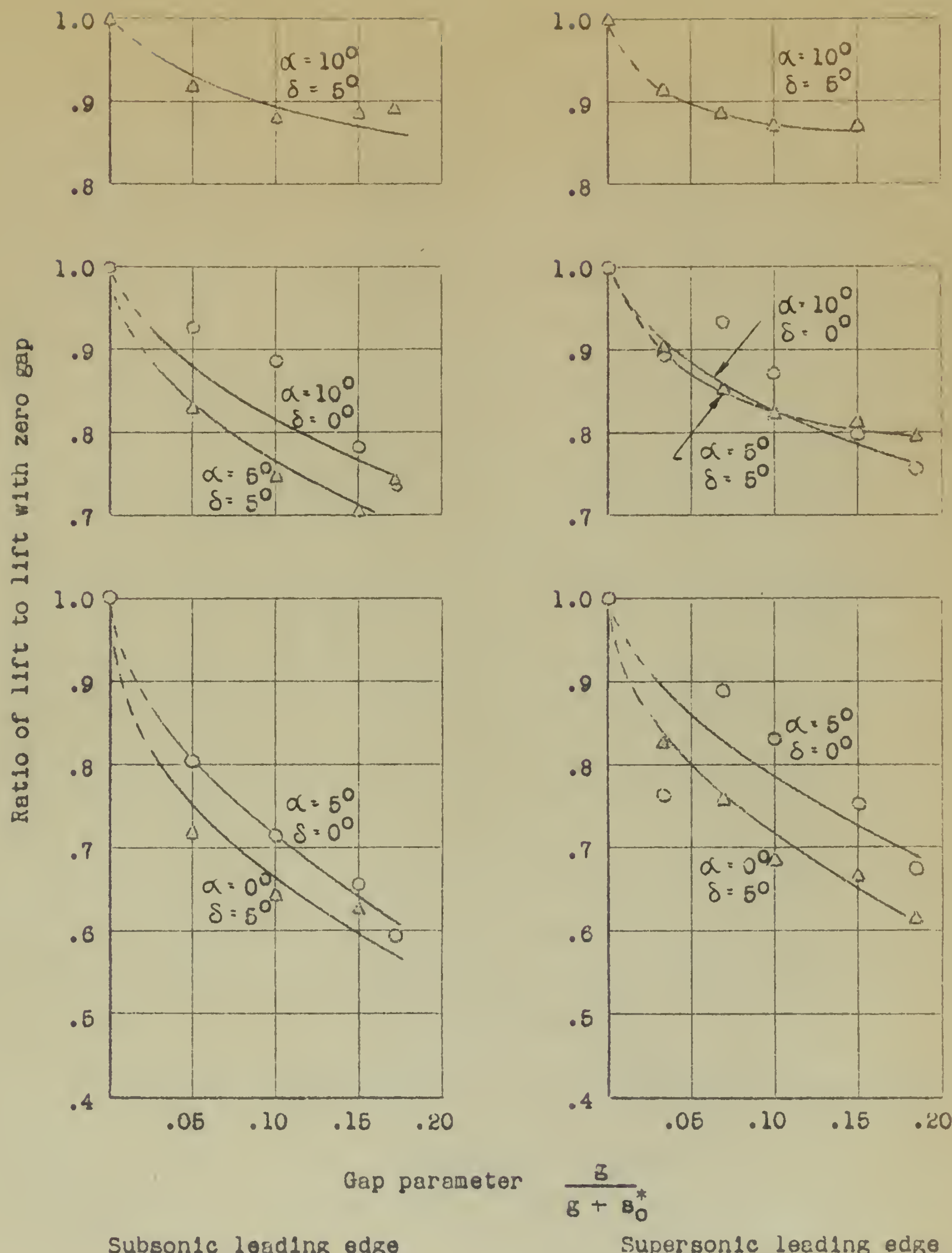


Figure 6. Variation of lift with gap for a wing body combination, body nose removed.

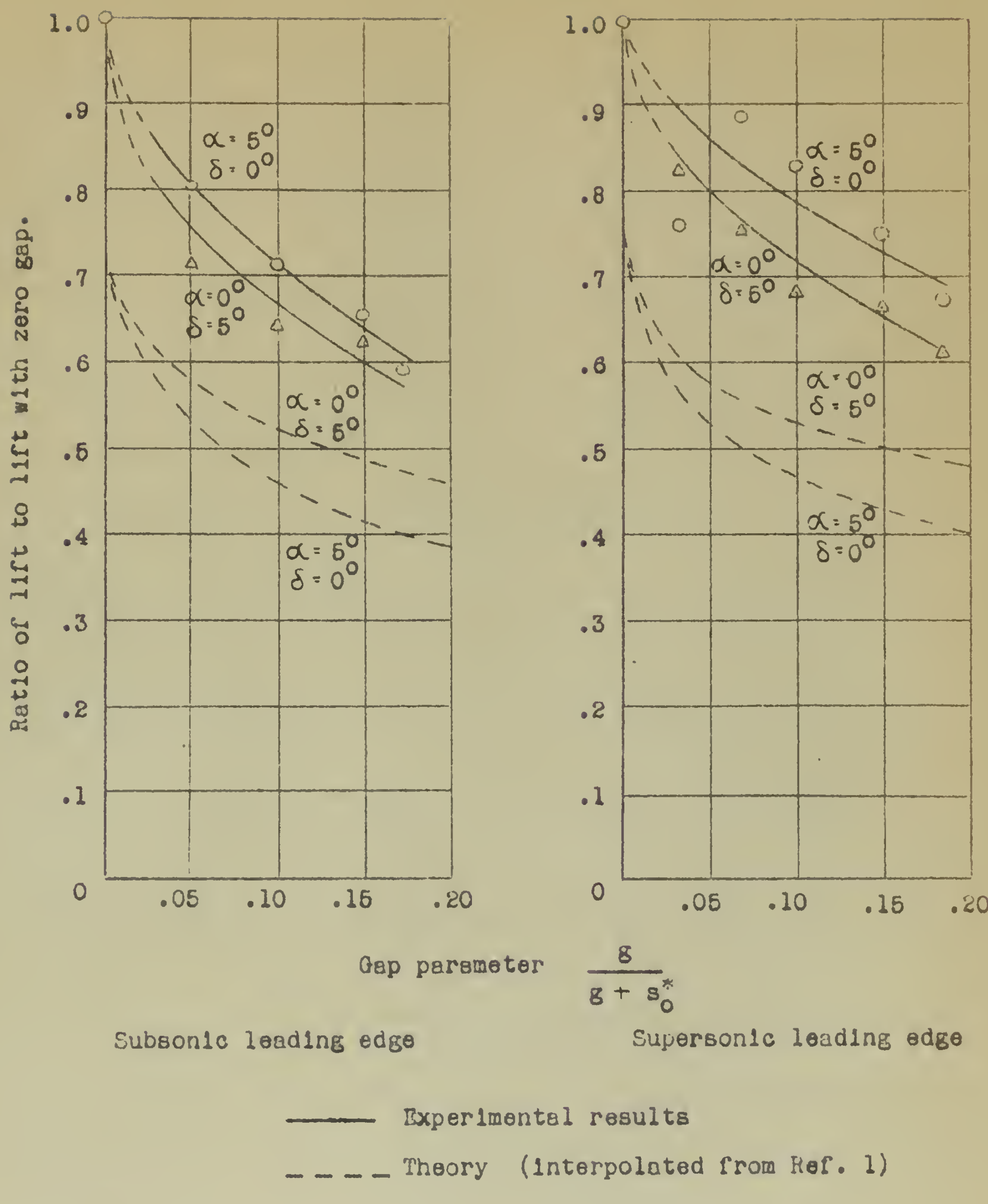


Figure 7. Variation of lift with gap for a wing body combination, body nose removed.

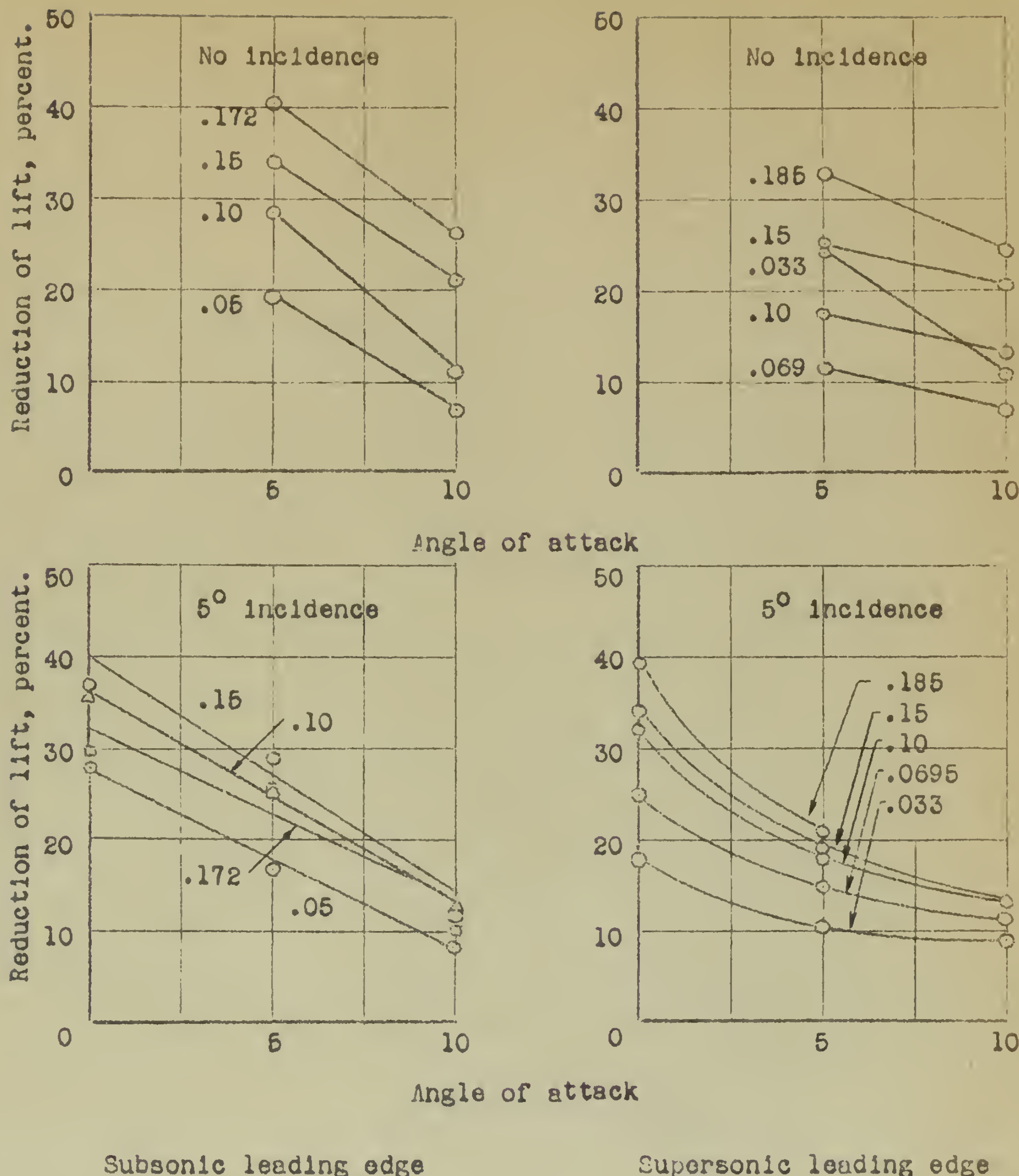
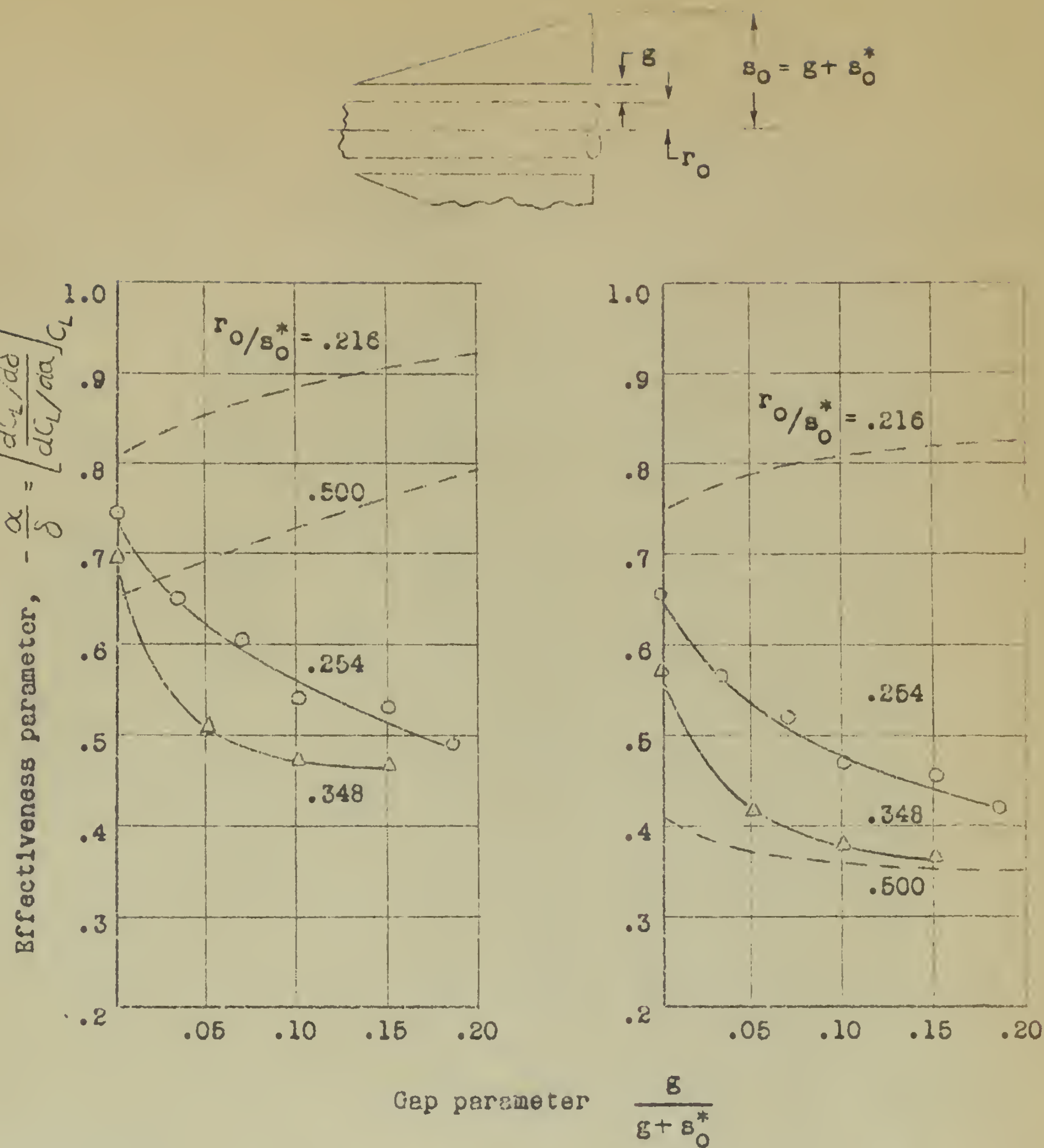


Figure 8. Variation of percent reduction of lift with angle of attack for various gap parameters.



Wing body, nose removed

Wing body, nose included

———— Experimental results

– – – – Theory (Ref. 1)

Figure 9. Variation of effectiveness parameter with gap for an all movable wing with various wing-body parameters, r_o/s_o^*

TABLE I

Subsonic leading edge wings

	Gap parameter $\frac{g}{g+g_o^*}$					Configuration	
	0	.05	.10	.15	.172	α	δ
Normal force lbs.	2.583	1.853	1.659	1.620	1.816	0	5
	4.928	4.115	3.747	3.520	3.266	5	0
	7.547	6.398	5.864	5.578	5.825	5	5
	9.821	9.750	8.894	8.040	7.663	10	0
	11.624	10.800	10.435	10.490	11.145	10	5
Normal force Coeff.* C_N	.2381	.1708	.1528	.1490	.1671	0	5
	.4535	.3789	.3450	.3244	.3005	5	0
	.6965	.5896	.5400	.5130	.5359	5	5
	.9038	.8470	.8190	.7410	.7050	10	0
	1.0713	.9953	.9610	.9647	.9890	10	5
Ratio of lift to lift with zero gap*	1.0	.7173	.6417	.6258	.7018	0	5
	1.0	.8022	.7124	.6577	.5944	5	0
	1.0	.8290	.7489	.7053	.7422	5	5
	1.0	.9271	.8872	.7834	.7355	10	0
	1.0	.9173	.8800	.8840	.8909	10	5
Percent reduction in lift*	0	28.3	35.5	37.5	29.9	0	5
	0	19.4	28.6	34.2	40.8	5	0
	0	17.1	25.1	29.3	25.9	5	5
	0	7.1	11.2	21.3	26.5	10	0
	0	8.1	12.0	11.7	10.1	10	5
Effectiveness parameter	.572	.414	.378	.365	.415	Body nose included	
	.695	.509	.471	.466	.521	Body nose removed	

* Body nose removed

TABLE II

Supersonic leading edge wings

	Gap parameter $\frac{g}{g+s_0^*}$						Configuration	
	0	.033	.0695	.10	.15	.185	α	δ
Normal force lbs.	4.256	3.796	3.561	2.909	2.846	2.887	0	5
	7.194	5.702	6.494	6.461	5.619	5.142	5	0
	12.007	9.841	10.228	10.102	8.949	8.533	5	5
	14.126	12.829	12.979	12.243	11.365	11.179	10	0
	17.959	15.984	15.562	15.308	15.684		10	5
Normal force coeff.* C_N	.2506	.2150	.190	.1711	.1674	.1698	0	5
	.4237	.3344	.3824	.360	.3305	.3026	5	0
	.638	.5790	.550	.533	.5263	.5019	5	5
	.814	.721	.7644	.7201	.6684	.640	10	0
	1.02	.9404	.9159	.9003	.898	.	10	5
Ratio of lift to lift with zero gap*	1.0	.8260	.7582	.6828	.6680	.6137	0	5
	1.0	.7618	.8898	.8301	.7514	.6767	5	0
	1.0	.8999	.8506	.8218	.8104	.7957	5	5
	1.0	.8923	.9334	.8714	.7991	.7593	10	0
	1.0	.9137	.8872	.8703	.8699		10	5
Reduction in lift* percent	0	17.2	24.2	31.6	33.2	38.4	0	5
	0	23.8	11.0	16.9	24.6	32.2	5	0
	0	10.1	14.9	17.8	18.8	20.4	5	5
	0	10.7	6.7	12.8	20.1	24.0	10	0
	0	8.8	11.2	12.9	13.0		10	5
Effectiveness parameter	.655	.565	.523	.469	.457	.422	Body nose included	
	.746	.650	.605	.541	.531	.489	Body nose removed	

* Body nose removed